The Influence of Amplitude Limiting and Frequency Selectivity Upon the Performance of Radio Receivers in Noise*

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Summary—**This paper describes an experimental study of the relations which exist between the effectiveness of voice communication, measured in terms of the intelligibility of received speech, and the amplitude- and frequency-selective characteristics of amplitude-modulation receivers. The results lead to the following conclusions:**

(1) Amplitude limiters are ineffective against fluctuation noise. Against impulse noise, however, they provide marked improvement in performance if they are incorporated in receivers with appropriate selectivity characteristics.

(2) When no limiter is used, best performance in the presence either of fluctuation noise or of impulse noise is provided by narrow-band circuits, but the advantage of narrow-band circuits over wide-band circuits is small.

(3) When a limiter is used, best performance against fluctuation noise is again provided by narrow-band circuits, and again the advantage of narrow-band circuits over broad-band circuits is small. For optimal reception in the presence of impulse noise, however, the selectivity curve of the circuits preceding the limiter must have gradually sloping skirts. When a limiter is used, therefore, advantage rests with broad-band rather than with narrow-band circuits.

I. INTERFERENCE

THE FLUCTUATION noise used in the experiments was generated with the aid of a 6D4 gas tube and wide-band amplifiers. The spectrum, approximately uniform from 100 to 5000 kilocycles, covered the frequency range important for these tests, which were conducted at carrier frequencies of 465 and 520 kilocycles.

The impulse noise consisted of pulses of constant amplitude, spaced irregularly in time. The average number of pulses per second was approximately 1000, and the irregularity of spacing was such that there were few 1-second intervals with less than half, or more than twice, that number of pulses. The spectrum of the impulse noise was approximately uniform from 100 to at least 20,000 kilocycles. Noise with these characteristics was generated by an irregularly triggered thyratron circuit which provided output pulses of approximately 0.02-microsecond duration.[1]

II. AMPLITUDE LIMITING

The amplitude limiter used in the experiments was a simple series-diode circuit, incorporated into the receiver at a point immediately following the detector. A schematic diagram of the limiter and its connection to the detector and to the cathode-follower output circuit is shown in Fig. 1. The limiter itself operates only upon the negative side of the audio wave, clipping off extreme negative peaks in the received signal.

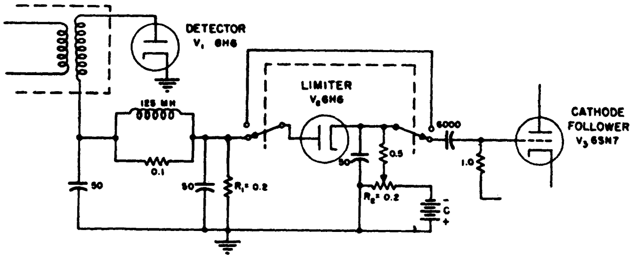

Fig. 1—Schematic diagram showing the amplitude limiter and its connection to the detector. Identical limiting circuits were used in the two test receivers. Values of resistance are in megohms, values of capacitance in micromicrofarads.

The action of the diode detector limits the positive swing at an amplitude level corresponding to 100 per cent modulation when the noise limiter is not connected. When the noise limiter is switched into the circuit, this positive-swing limitation is made more severe because part of the negative bias from R_2 is thrown across R_1. This bias shifts the amplitude at which detector limitation takes place with the result that the detector clips the positive swings approximately as much as the noise limiter clips the negative swings. Thus, although the noise limiter uses only a single diode, the circuit provides full-wave limitation. In the main series of experiments reported herein, the circuit was so adjusted that the limiting took place at an amplitude corresponding approximately to 50 per cent modulation.

III. FREQUENCY SELECTIVITY

The frequency-selective circuits used in the experiments provided control over two characteristics of the selectivity curve: (1) the bandwidth, important in determining the over-all level of the interference passed by the receiver; and (2) the slope of the skirts of the curve, important in determining the wave form of the output when the interference is impulsive. In order to obtain a wide range of control over each of these characteristics, two test receivers were prepared. Receiver I was a laboratory set which consisted of a variable-band

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[1] C. J. Mullin and H W. Rudmose, Psycho-Acoustic Laboratory Report PNR-8, pp. 1–29; October 28, 1945. This report describes in detail the generator, Electro-Acoustic Laboratory Static Generator Model X-1, and may be obtained through the Office of Technical Services, United States Department of Commerce, Washington, D. C.

radio-frequency amplifier and the detector and audio circuits shown in Fig. 1. Receiver II consisted of the (modified) intermediate-frequency amplifier of a Hallicrafters SX-28-A receiver, followed by detector and audio circuits which were duplicates of those in receiver I.

Control over bandwidth was achieved by varying the coupling of the interstage transformers, and control over the slope of the skirts of the selectivity characteristics by varying the dissipation factor ($D=1/Q$) of the coupling circuits. Actually, changes in coupling produce some effect upon slope and changes in Q produce some effect upon bandwidth, but these effects are secondary.

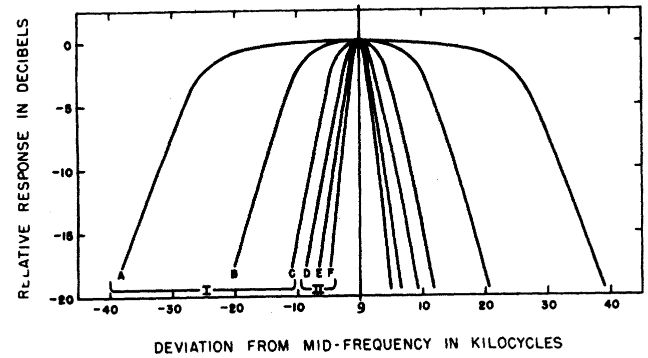

Fig. 2—Frequency-selective characteristics of the test receivers. The curves labeled *A*, *B*, and *C* are three of the selectivity characteristics which could be obtained with receiver I. Those labeled *D*, *E*, and *F* are three additional characteristics provided by receiver II.

Selectivity characteristics representative of those provided by the two test receivers are shown in Fig. 2. Three of the curves (*A*, *B*, and *C*) were obtained with receiver I; the other three (*D*, *E*, and *F*) were obtained with receiver II. It was possible, with other adjustments of the test receivers, to provide other characteristics besides those shown—in particular, to set up characteristics with the same bandwidths at half-power but with different slopes, and characteristics with the same slopes but different bandwidths.

IV. Listening-Test Procedure

In studying the influence of amplitude limiting and frequency selectivity upon intelligibility, two types of listening tests were used: threshold tests and articulation tests. Threshold tests were employed in preliminary experiments in order to determine, under a variety of experimental conditions, the signal-to-interference ratios required for satisfactory reception of speech. Articulation tests were then employed in the principal series of tests to provide, under a more restricted set of conditions, quantitative measures of intelligibility.

Threshold Tests

In the threshold tests, meaningful paragraphs were read over the communication system to the listeners, who in some instances worked individually and in other instances as a group. The radio-frequency signal-to-interference ratio was adjusted until the listeners could follow with little difficulty the sense of the paragraphs. The signal-to-interference ratio thus determined is referred to as the "threshold of intelligibility."

Articulation Tests

In the articulation tests, the announcers read discrete words instead of meaningful material, and the observers, listening in a group, wrote down the words as they heard them. The test vocabulary consisted of 1000 monosyllabic words, organized into twenty 50-word sets approximately equal in difficulty. The words of each set were "scrambled" to provide a large number of equivalent test lists.[2] Each test word was read as part of the *carrier sentence:* "You will write __________." The results of the articulation tests were expressed in terms of the percentage of the test words recorded correctly. Percentages for two talkers, each reading 50 words to the group of listeners, were averaged to determine the value of "per cent word articulation" for each experimental condition.

The test setup shown in Fig. 3 was used for both the threshold and the articulation tests.

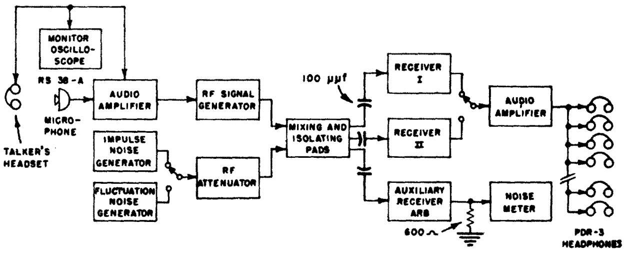

Fig. 3—Schematic diagram of test setup. The arrangement provided a speech-modulated carrier and either of two types of noise. The carrier and the noise were added in a resistive mixing circuit and applied together to the input terminals of the test receivers. An auxiliary receiver and noise meter, calibrated with the aid of the signal generator, were used in measuring the carrier-to-noise ratios.

Speech-modulated carrier: The amplitude-modulated carriers (520 and 465 kilocycles, 50 microvolts) were obtained by modulating a General Radio Type-805-A signal generator with a speech signal produced externally. The speech modulation was provided by two experienced talkers who read the test words into a carbon microphone (Navy Type RS 38-A) and monitored their speech at a level suitable for communication under adverse conditions. The speech amplifier was adjusted to provide 100 per cent modulation of the carrier on the average instantaneous peaks of the speech wave. Both sidebands were used.

Interference: Fluctuation noise and impulse noise were generated as described above. The intensity of the interference was controlled by a radio-frequency attenuator connected at the output of the interference generator. This attenuator permitted either continuous variation or variation in 5-decibel steps.

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[2] The lists, known as the Psycho-Acoustic Laboratory PB Lists, were developed in connection with an extensive wartime program in which articulation tests were used to evaluate communication systems.

Method of mixing: The speech-modulated carrier and the interference were mixed in a resistive network and fed separately (from isolating pads of 10 ohms output impedance through 100-micromicrofarad capacitors) to the test receivers and to the receiver used in measuring the signal-to-interference ratio.

Signal-to-interference ratio: In the tests, the carrier intensity was held constant at 50 microvolts, and various signal-to-interference ratios were obtained by varying the interference level. The intensity of the interference (equivalent noise sideband input) was measured with an auxiliary receiver (Navy Type ARB, pass band approximately 10 kilocycles wide) and an output meter (RCA Type 302-B). The level was determined by substituting a carrier which was modulated 100 per cent at 400 cycles and varying its intensity until it produced the same indication on the noise meter as did the interference.[3]

Headsets and listeners: The audio amplifier of the test receiver was adjusted to deliver 5 milliwatts to each headset. The headsets, which consisted of Permoflux PDR-3 headphones mounted in small sponge-rubber cushions (MX-41/AR), provided approximately uniform response to 4500 cycles. With 5 milliwatts input, the output level was 115 decibels above 0.0002 dyne/cm^2.

Except in some of the preliminary work in which the experimenters served as listeners, the listeners were a group of nine to twelve women who had, in previous experiments, made articulation scores which agreed very closely with those of a comparable group of men. The listeners were seated in a relatively quiet room adjoining that in which the test equipment was set up. They could neither watch the talker nor hear his voice directly as he read the test words.

V. Results

Threshold-of-Intelligibility Tests

The carrier-to-noise ratios required to reach the threshold of intelligibility in the presence of impulse noise (1000 pulses per second) with six different bandwidths and five different amounts of amplitude limiting are shown in Fig. 4. The selectivity characteristics were those shown in Fig. 2. Four of the clipping levels corresponded, as indicated in the figure, to 18, 32, 56, and 100 per cent modulation, and the fifth was "no clipping." Fig. 4 shows (1) that the minimum carrier-to-noise ratio required for satisfactory reception was, in general, markedly lower when amplitude limiting was introduced than when it was not; (2) that the advantage provided by amplitude limiting depended markedly upon the width of the pass band; and (3) that the amplitude level at which limiting took place was not, within the range tested, a critical factor. Inasmuch as a level corresponding to about 50 per cent modulation gave consistently good results, that adjustment of the amplitude limiter was adopted as one of the two amplitude-limiting characteristics to be used in the principal series of tests. The other characteristic, no amplitude limiting, was obtained by disconnecting the limiter.

At the top of Fig. 4, the duration of the output pulses (measured at a level approximately 20 decibels below the peaks) has been indicated along a scale which parallels the (lower) scale of half bandwidth. It is not clear from these data whether the significant relation is between performance (with limiter) and bandwidth, or between performance and pulse duration. In order to distinguish between bandwidth and pulse duration as factors influencing the effectiveness of amplitude limiting, threshold tests were conducted with several additional combinations of the adjustments of coupling and *Q.* Some of these combinations provided equal bandwidths, as measured at the half-power points, but different pulse durations. Others provided equal pulse durations but different bandwidths. The results indicated clearly that, with a given type and amount of interference, the duration of the output pulses, as measured near the base of the pulse, is the primary factor in determining the effectiveness of amplitude limiting.

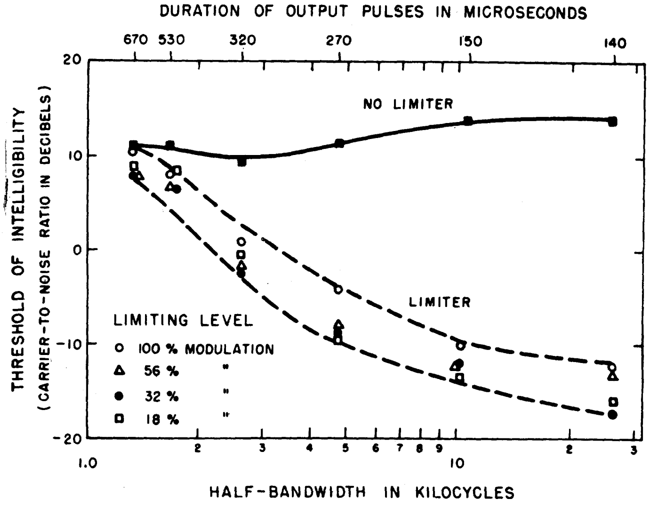

Fig. 4—Threshold-of-intelligibility curves showing the superior performance of broad-band circuits when used in conjunction with amplitude limiting against impulse interference. Performance is measured in terms of the carrier-to-noise ratio required for usable reception. The upper solid curve indicates that, when no limiter is used, slightly higher ratios were required with broad-band circuits than with narrow-band circuits. But, as shown by the lower dashed curves, broad-band circuits were much the more effective when an amplitude limiter was employed.

Using the variety of selectivity characteristics just described, threshold tests were conducted also with fluctuation noise. The differences between the thresholds for the various selectivity curves were very small, and it was apparent that neither frequency selectivity nor amplitude limiting was markedly effective against fluctuation noise.

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[3] Actually, the carrier set up to provide equivalent output was modulated only 56 per cent, and a correction was made by multiplying the carrier intensity by 0.56.

Articulation Tests

The relationships obtained between per cent word articulation and carrier-to-interference ratio are presented in Figs. 5 and 6. These curves bear out the conclusions based on the threshold tests and afford more quantitative indexes of the performance provided by the several combinations of frequency-selective and amplitude-limiting characteristics.

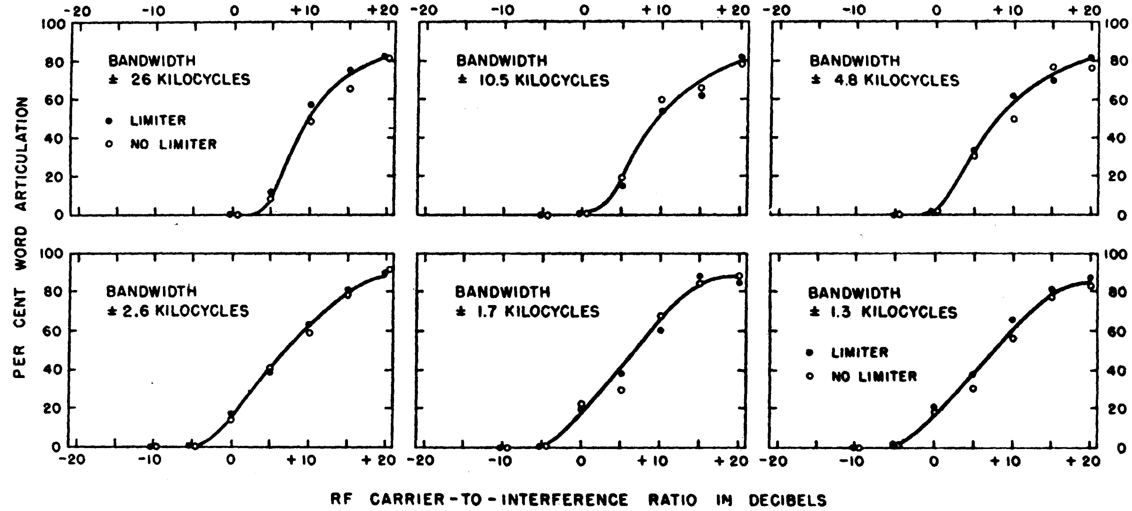

Fig. 5—Results of articulation tests with fluctuation noise. Word articulation is plotted as a function of radio-frequency carrier-to-interference ratio for the six frequency-selective characteristics shown. In the tests with the limiter (filled circles) the audio wave was limited sharply at the level corresponding to 50-per-cent modulation. In the tests in which the limiter was not used, the only amplitude limitation was that introduced by the normal action of the detector.

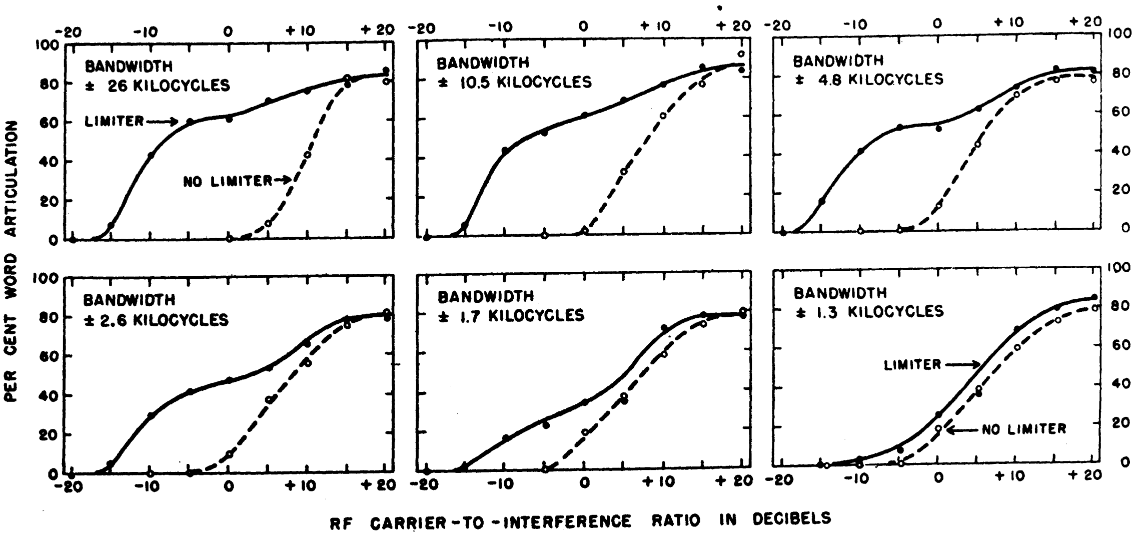

Fig. 6—Results of articulation tests with impulse noise. These results were obtained with the same frequency-selective and amplitude-limiting circuits as those shown in Fig. 5, but in the presence of irregularly spaced pulses (average pulse-repetition frequency 1000 pulses per second) instead of fluctuation noise.

In the presence of fluctuation noise (Fig. 5) the effect of amplitude limiting upon intelligibility is essentially nil, no matter what the bandwidth. Performance is better with narrow-band coupling circuits than it is with broad-band coupling circuits, whether amplitude limiting is used or not; the advantage of narrow-band circuits is never great, however, and it appears to be of practical significance only when the carrier-to-interference ratio is low.

In the presence of impulse noise (Fig. 6), amplitude limiting is highly effective in improving performance if the frequency-selective circuits which precede the limiter have the (broad-band, low-Q) characteristics which are required to preserve the spike-like wave form of the pulses.

In conjunction with narrow-band coupling circuits which broaden the pulses, amplitude limiting is relatively ineffective. If no amplitude limiter is used, however, some advantage results from the employment of narrow-band coupling circuits. This advantage is roughly equivalent to that found in the tests with fluctuation noise.

VI. DISCUSSION OF RESULTS

Frequency Selectivity Without Amplitude Limiting

In the presence of uniform spectrum noise, noise output power is directly proportional to bandwidth.[4] It is therefore not at all surprising to observe that, in the presence of fluctuation noise or in the presence of impulse noise when no limiter is used, narrow-band circuits provide better performance than broad-band circuits. But it is surprising to find that, even when bandwidths in the ratio of 1 to 20 are considered, the margin in favor of narrow-band circuits is so small.

It must be noted that, in the experiments reported herein, not all of the broad-band noise output reached the listeners' ears because the earphones were relatively insensitive at frequencies above 5000 cycles. But supplementary listening tests indicated that intelligibility was not noticeably changed when earphones with uniform response to 7500 cycles were substituted, and it is probable that it would not have been altered markedly if the headphones had passed the highest audio frequencies in the detector output. The significant factor appears to be not the frequency response of the audio equipment but the "masking" in the listener's auditory system. It is well known that low-frequency sounds mask high-frequency sounds, but high-frequency sounds do not mask low-frequency sounds.[5] Noise components above 2000 cycles are, therefore relatively ineffective in masking speech, and noise components above 4000 cycles may be disregarded in so far as influence upon intelligibility is concerned. The disadvantage of broad-band receiving circuits is, in this respect, much less pronounced than uncritical consideration of noise power as noise power—without regard to frequency—would suggest.

Frequency Selectivity and Amplitude Limiting

In considering the action of the amplitude limiter against interference, it is helpful to think in terms of amplitude selectivity, i.e., of discrimination in favor of signal and against noise on the basis of some characteristic difference between the amplitude patterns of the signal and the noise. When the problem is considered in these terms, it is apparent that amplitude selectivity can be effective in improving performance only if a characteristic difference between the wave forms of signal and noise exists. It is apparent, also, that for maximal effectiveness the particular type of amplitude selectivity chosen must be one appropriate for the difference in wave form.

Since both speech and fluctuation noise have continuous, irregular wave forms, and since their ratios of peak[6] to root-mean-square amplitude are, on the average, about equal, it is not surprising that amplitude limiting provides no marked improvement in performance against fluctuation noise. Against highly peaked impulse noise, on the other hand, limiters are effective because, simply by clipping off the peaks, a considerable reduction in noise intensity can be achieved with very little disruption of the speech wave—and low-Q coupling circuits maintain the abrupt, transient wave form of impulse noise.

The relation between the effectiveness of amplitude limiting and the bandwidth of the circuits which precede the limiter is thus a reflection of the relation between bandwidth and pulse duration.[7] The way in which pulse duration controls intelligibility when amplitude limiting restricts all of the output pulses to the same amplitude may, for practical purposes, be thought of as follows: Each pulse blanks out the speech signal during a short time interval. As the duration of the pulse is increased, the disruptive effect upon intelligibility is increased. As the duration is increased still further, each pulse fills up a considerable time interval and successive pulses start to overlap. When this occurs the interference loses the characteristics of impulse noise and takes on the characteristics of fluctuation noise. There is then no distinguishing characteristic on the basis of which the amplitude limiter may discriminate against the noise and in favor of the speech, and amplitude limiting becomes ineffective.

It is unfortunate that the type of selectivity characteristic which is required in order to permit effective amplitude limiting in the presence of impulse noise is just the type of selectivity characteristic which is least effective in rejecting adjacent-channel signals. However, a certain amount of impulse interference is encountered even in the range of very-high frequencies in which it has not proved feasible to use narrow pass bands. The present results would suggest, therefore, that very-high-frequency amplifiers be designed with low-Q circuits rather than with staggered or overcoupled high-Q circuits. Furthermore, even in medium- and low-frequency applications it is sometimes more important to minimize impulse interference than to avoid adjacent-channel interference. In such an event, a broad selectivity characteristic would be preferable to a narrow one.

The advantages of effective amplitude limiting can perhaps be reconciled to some degree with the advantages of a narrow over-all pass band by incorporating the amplitude limiter into the intermediate-frequency section of the receiver.[8] Or, the selective circuits of the receiver might be so arranged that their characteristics could be altered, perhaps automatically, in accordance with the requirements for optimal handling of the received wave.

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[4] John R. Carson, "Selective circuits and static interference," *Trans. A.I.E.E.* (*Elec. Eng.*, June, 1924), vol. 43, pp. 789–797; June, 1924.

[5] S. S. Stevens and Hallowell Davis, "Hearing: Its Psychology and Its Physiology," John Wiley and Sons, New York, N. Y., 1938.

[6] The term "peak amplitude" as used here should be qualified. It is convenient to consider not the highest amplitude ever to be reached by the wave, but the highest amplitude to be exceeded some fixed small percentage (e.g., 1 per cent) of the time.

[7] Martin Wald, "Noise suppression by means of amplitude limiters," *Wireless Eng.*, vol. 17, pp. 432–438; October, 1940.

[8] J. J. Lamb, "Silencing circuits for radio receivers," United States Patent No. 2,101,549.